B Physics at Hadron Colliders

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Hadron colliders have played, and will continue to play, a crucial role in the understanding of CP violation. Their impact is expected to be especially important in the study of CP asymmetries in rare decays and the B_s meson. The experimental challenge and reach of current and future experiments is discussed.

1 Introduction

Almost forty years have past since the first observation of CP violation in the kaon system. Recently, CP violation has been clearly established in the B system with the measurement of sin 2β at the e^+e^- B-factories. The average value of $\sin 2\beta = 0.734 \pm 0.054$ measured by the Belle and BaBar experiments [1] is in excellent agreement with the expectation of the standard model fits[2] which are based on the Cabibbo, Kobayashi and Maskawa (CKM) ansatz [3]. In fact, already in 1998 several groups predicted a value of $\sin 2\beta = 0.72 \pm 0.02$ which was remarkably close to the current world average[4].

Despite the great success of the CKM description of CP violation it is clear that we have not yet answered the fundamental questions about the origin of the hierarchical pattern of the CKM matrix elements that we are now confirming experimentally. A major goal of present and future experiments is to fully tests the CKM ansatz. Measurements at hadron colliders have the potential to facilitate this task by providing a unique laboratory to study CP violation in the B_d and B_s system, mixing of the B_s meson, and rare B decays. Many studies on the impact of hadronic machines in B physics have recently taken place and were a source for this talk.[5,6]

1.1 CP Violation in the Standard Model and the CKM Matrix

The CKM matrix, V_{CKM}, is a unitary matrix [3] that transforms the mass eigenstates to the weak eigenstates. The matrix can be expressed in terms of four independent phases which are not

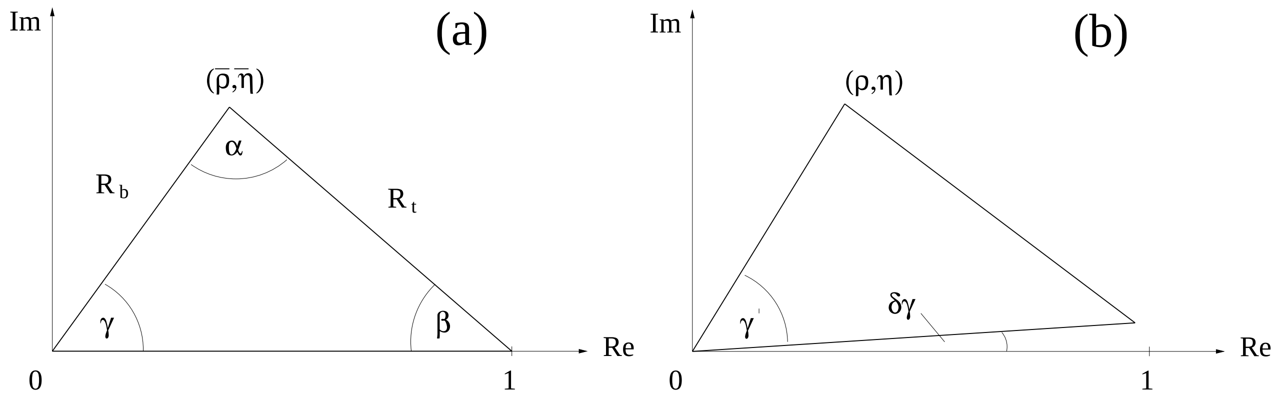

Figure 1: The unitary triangles (db) and (ut) in complex space.

predicted in the standard model but have to be determined experimentally. In the Wolfenstein parameterization [7] the matrix can be written in terms of λ, A, ρ and η as:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx$$

$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta(1-\frac{\lambda^2}{2})) \\ -\lambda & 1-\frac{\lambda^2}{2} - i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The expression is accurate to order λ^3 in the real part and λ^5 in the imaginary part. The sine of the Cabibbo angle, λ, is measured in semileptonic kaon decays, $\lambda = |V_{us}| = 0.2196 \pm 0.0026$, and plays the role of an expansion parameter. A can be determined in $b \to c$ decays since $A \approx V_{cb}/\lambda^2$ and $V_{cb} = (41.2 \pm 2.0) \times 10^{-3}$. Only λ and A are measured precisely. The measurements of $\sin 2\beta$, ϵ in Kaon decays and B mixing constraint η and ρ with some accuracy and the PDG 2002 fit[8] yields $\bar\rho$=$\rho(1-\frac{\lambda^2}{2})$= 0.22 ± 0.10 and $\bar\eta$= $\eta(1-\frac{\lambda^2}{2})$=$0.35 \pm 0.05$. The parameter η represents the CP-violating phase and must be different from zero to accommodate CP violation in the standard model.

The unitarity of the CKM matrix implies that there are six orthogonality [9] conditions between any pair of columns or any pair of rows of the matrix:

$$\begin{array}{rcll} V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* & = & 0 & (db) \\ V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* & = & 0 & (sb) \\ V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* & = & 0 & (ds) \\ V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* & = & 0 & (ut) \\ V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* & = & 0 & (ct) \\ V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* & = & 0 & (uc) \end{array}$$

where the quark pair in parenthesis indicates the row or column under consideration. Each of the orthogonality conditions requires the sum of three complex numbers to vanish and can be represented as a so called "unitarity triangle" in complex space. Only triangles (db) and (ut) have three large angles. The two triangles are drawn in Fig. 1.

The apex of the triangles have coordinates (ρ, η) or ($\bar\rho, \bar\eta$) as shown in figure 1. The three angles of the unitarity unitarity triangle (db) are :

$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \qquad \gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

while the three angles of the triangle (ut) are:

$$\alpha' = \arg\left[-\frac{V_{td}V_{ud}^*}{V_{tb}V_{ub}^*}\right] \qquad \beta' = \arg\left[-\frac{V_{ts}V_{us}^*}{V_{td}V_{ud}^*}\right] \qquad \gamma' = \arg\left[-\frac{V_{tb}V_{ub}^*}{V_{ts}V_{us}^*}\right]$$

Measurements of weak decays of B hadrons determine the magnitudes of the sides of the triangles:

$$R_b = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right| \qquad R_t = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

while CP asymmetries and rates of B meson decays determine the three angles.

The angles of the two unitarity triangles are also related by the following equations:

$$\alpha' = \alpha \qquad \beta' = \beta + \arg\left[V_{ts}\right] \qquad \gamma' = \gamma - \arg\left[V_{ts}\right]$$

Therefore if we define $\delta\gamma = \gamma' - \gamma$ then $\delta\gamma = \eta\lambda^2$. Therefore the two triangles are identical at leading order in the Wolfenstein expansion. However we expect that future high statistics dedicated experiments will be sensitive to these differences and further probe the CKM matrix.

At hadron colliders the B_s mesons is copiously produced and therefore there is an opportunity to measure the B_s asymmetries. The unitarity triangle (s,b) is squashed since the first side is much shorter than the other two and the opposing angle:

$$\beta_s = \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] = \lambda^2\eta + \mathcal{O}(\lambda^4)$$

is of the order of one degree. Therefore in the standard model we expect the B_s CP asymmetries to be smaller than in the B system. On the other hand these asymmetries are sensitive to new physics and therefore the measurement of β_s is especially important.

The goal of B physics in the next decade is to overdetermine the CKM matrix to test the consistency of the standard model and hopefully discover new physics. Signs of physics beyond the standard model could appear as:

- The standard model predictions for the branching fractions and the CP asymmetries will disagree with the experimental measurements and $\alpha + \beta + \gamma \neq \pi$
- The values of ρ and η determined from B decays disagree with the values obtained from K decays
- Decays forbidden or rare in the standard model occur at larger rates than expected.
- CP asymmetries larger than expected in the standard model.

B_s mesons are expected to have a special role in this effort since it has been suggested that β_s can be measured in $B_s \to J/\psi\eta(')$.

2 B production at hadron colliders

Electron positron B-factories running at the Υ(4S) which is at the threshold for open beauty production have been very effective in the study of B mesons. Recently with the advent of precise silicon detectors crucial measurements have also been performed at LEP and at hadron colliders.

B meson production at the Υ(4S) is dominated by $B^0\bar{B}^0$ and B^+B^- final states. The cross section for $b\bar{b}$ production $\sigma_{b\bar{b}}$ is 1.15 nb and the signal to background defined as the ratio $S/B = \sigma_{b\bar{b}}/\sigma_{total}$ is 0.25. The B-factories operate in an asymmetric beam configuration that

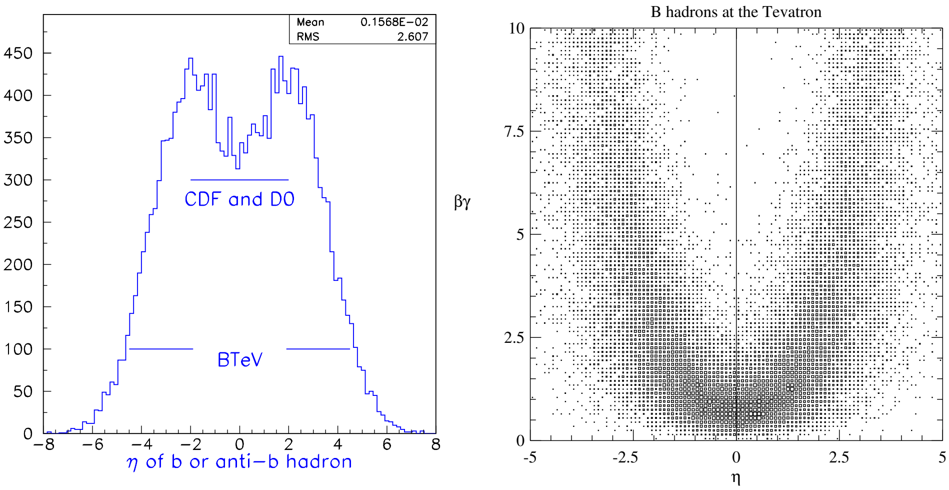

Figure 2: Left: The B production cross section versus $\eta = -\ln(\tan\theta/2)$. Right: The B production cross section as a function of the lorentz boost $\beta\gamma$ and η.

allows for the production of the Υ(4S) boosted along the beam axis. The separation between the two B's along the beam axis is 200 and 260 μm at Belle and BaBar respectively. These machines are ideally suited to study CP violation in $J/\psi K_s^0$, for the precision determination of V_{cb} and V_{ub} in semileptonic decays and rare decays of B mesons into final states which include neutral pions and photons such $B \to K^*\gamma$.

Electron positron colliders running at the Z^0 such as LEP and SLD have the advantage of a larger boost that allows a better separation of the decay vertices of charm and beauty hadrons. The B meson mean decay length at the Z^0 is 2.7 mm. The cross section is $\sigma_{b\bar{b}}$ of 7 nb and the S/B is similar to the one obtained by the B-factories. At LEP and SLD, because of the higher energy available, all B hadron species are produced including B_s, B_c, Λ_b and Ω_b. These colliders have contributed significantly to our current knowledge of B hadrons lifetimes and mixing.

The cross section for $b\bar{b}$ production at the Tevatron, a hadronic machine running at a center of mass energy of 2.0 TeV, is about 100 μb. Unfortunately the background is also large and the S/B is only about 0.2%. At a center of mass energy of 14 TeV, at which the Large Hadron Collider will operate, the $b\bar{b}$ cross section and the S/B will increase to 400 μb and 0.4%. Specialized triggers are necessary in order to write the events of interest to tape. The average decay length of produced b hadrons is a few mm because of the momentum boost. Similarly to LEP, a full spectrum of b mesons and baryons are produced at hadronic machines.

Two kinds of b experimental configuration are considered for hadron colliders as shown in Fig. 2. The first is a central all-purpose detector such as CDF and D0. This configuration is also implemented in CMS and ATLAS which will take data at the LHC. The bulk of the $b\bar{b}$ production is concentrated in the central rapidity region. Nonetheless forward going B mesons have much higher momentum and therefore longer decay length than B mesons produced in the central region. Dedicated forward b-experiments such as B-TeV and LHC-b are in the planning stage or under construction for operation at the Tevatron and the LHC respectively. Forward experiments exploit the correlation between the direction of the produced $b\bar{b}$ and the boost direction. Moreover dedicated experiments can provide better particle identification and neutral pion identification.

3 Experimental issues

3.1 Trigger

The primary experimental issue of B physics at hadron collider is the triggering. The $b\bar{b}$ production rate at B factory operating at a luminosity $L = 10^{34} cm^{-2}s^{-1}$ is about 10 Hz while it is about 20 KHz at the Tevatron and 100 KHz at the LHC at $L = 10^{33} cm^{-2}s^{-1}$. During Run I of the Tevatron the CDF and D0 triggers relied on the presence of single and dilepton triggers such as $B \to J/\psi X$ and then $J/\psi \to \mu^+\mu^-$. Although the branching fraction for $B \to J/\psi X$ is only 1.15 % hadronic experiments have an advantage with respect to the B-factories because of the large production cross section available at hadronic machines.

In Run II of the Tevatron, that started in spring 2001, CDF has also implemented a new high precision trigger that allows for the selection of events with detached vertices. These triggers based on precise vertex information from silicon detectors will also be adopted by CMS, ATLAS, LHCb and BTeV. They allow a factor of about 100 enrichment in b content at the trigger level. Moreover this displaced vertex trigger method is crucial for selecting hadronic decays such as $B \to \pi^+\pi^-$ and $B_s \to D_s^-\pi^+$.

3.2 Flavor Tagging

The measurement of CP violation and mixing requires the identification of the flavor of the B meson at the time of production. Tagging algorithms are evaluated in terms of efficiency ϵ for determining the flavor tag (b or $\bar{b}$) and the probability that the tag is correct. The quality of the tag is evaluated by defining the tagging dilution as $D = (N_R - N_W)/(N_R + N_W)$ where $N_R(N_W)$ is the number of right (wrong) tags. The observed asymmetry is reduced with respect to the true asymmetry by the dilution D and $A_{CP}^{obs} = DA_{CP}$. Therefore the maximum sensitivity can be achieved when the dilution is large and a perfect tagging algorithm will have a dilution $D = 1$. The statistical uncertainty on $\sin 2\beta$ is inversely proportional to $\sqrt{\epsilon D^2}$. The statistical uncertainty is also proportional to $\sqrt{S^2/(S+B)}$ where S is the number of signal events and B is the number of backgrounds events. Therefore the data sample should be chosen to maximize the signal and minimize the background.

Several tagging methods are used to improve ϵD^2. The opposite side tagging algorithms identify the flavor of the *opposite* B in the event at the time of production. If one knows that the other b hadron contains a b quark then the signal B meson must contain at $\bar{b}$ quark. Several methods of opposite side tagging can be employed: soft lepton tag (SLT), soft kaon tagging and jet-charge tag (JETQ).

The soft lepton tag associates the charge of the lepton (e or μ) from semileptonic decays with the flavor of the parent B meson as $b \to X\ell^-$ compared to $\bar{b} \to X\ell^+$. Since we are tagging the opposite B meson, its flavor is anti-correlated with the flavor of the B-meson that decays to the mode under study. Hence a $\ell^-(\ell^+)$ tags a $\bar{b}(b)$ like $B^0(\bar{B}^0)$. The branching fraction for semileptonic decays is about 10% into each e and μ channels. There is also dilution because of sequential decays where a b hadron decays into a c hadron which then decays semileptonically. However the leptons from direct and sequential decays have different kinematic properties and a good separation can be achieved. Further dilution is caused by mixing since 17.4% of the B^0 will oscillate to a $\bar{B}^0$ before decaying. Moreover the B_s is fully mixed and will not provide any tagging power.

"Jet charge" or JETQ, tags the b flavor by measuring the average charge of the opposite side jet which is calculated as:

$$Q_{jet} = \frac{\sum_i q_i(\vec{p_i} \cdot \hat{a})}{\sum_i \vec{p_i} \cdot \hat{a}}$$

where q_i and $\vec{p_i}$ are the charge and momentum of track i in the jet and $\hat{a}$ is the unit vector along

the jet axis. On average the sign of the jet charge gives the flavor of the b quark that produced the jet.

Kaon tagging exploits charge of the kaon in the away side because of the decay chain $b \to c \to XK^-$ compared to $\bar{b} \to \bar{c} \to XK^+$. Since the product of branching fractions is large this tagger has a larger efficiency than the SLT but lower dilution. Excellent particle identification is necessary.

The same side tagging method or SST relies on the correlation between the B flavor and the charge of the nearest pion in the fragmentation chain. Such a correlation can arise from the fragmentation processes which form a B meson from a $\bar{b}$ quark and from the decay of an excited B meson state (B^{**}). In the fragmentation a $\bar{b}$ quark forming a B^0 can combine with a d in the hadronization leaving a $\bar{d}$ which can form a π^+ with a u quark from the sea. The excited B state will decay $B^{**+} \to B^{(*)0}\pi^+$. Therefore in both cases a B^0 ($\bar{B}^0$) meson is associated with a positive (negative) particle respectively.

The dilution parameters for all tagging algorithms can be measured on calibration samples. At hadronic machines the strong interaction creates $b\bar{b}$ pairs at sufficiently high energy that the B mesons are largely uncorrelated. For example, the b quark could hadronize as a $\bar{B}^0$ while the $\bar{b}$ could hadronize as a B^+, B^0, or B_s^0 meson. Therefore we can use a samples of $B^\pm \to J/\psi K^\pm$ decays to measure the tagging dilutions for the opposite side algorithms. The performance of the same side tagging methods is usually evaluated by tagging $B \to \nu\ell D^{(*)}$ decays and by measuring the time dependence of $B^0\bar{B}^0$ oscillations in this high statistics sample and in a lower statistics sample of $B \to J/\psi K^{*0}$. The tagging methods have different characteristics. The lepton tagging has relatively low efficiency but good dilution. The same side tagging and the jet charge tagging are more efficient but have lower dilution. Kaon tagging performance will depend crucially on the particle identification capabilities of the specific detectors. The different tagging information can be combined to obtain a more powerful performance. Such combination must account for correlations. In general flavor tagging at hadron collider experiment achieves an effective efficiency $\epsilon_{eff} = \epsilon D^2 \approx 10$ % while at a b-factory it is about 30%. These expectations are confirmed by the CDF tagging performance in run I where CDF used most of these methods but the kaon tagging for the measurement of B_d mixing and $\sin 2\beta$.

3.3 Measurement Error on Proper Decay Time

The b hadron proper decay time is evaluated by measuring the decay length which is the distance between the primary vertex and the secondary vertex where the b hadron decayed. The proper decay time is $t = Lm/pc = L/\beta\gamma c$ where L is the decay length, p and m is the reconstructed momentum and mass of the b hadron, c is the speed of light, and β and γ are the b hadron Lorentz parameters. The uncertainty in the primary vertex position, the secondary vertex position, and the b hadron momentum all contribute to the measurement error on the decay length. Since the secondary vertex position uncertainty is larger than the primary vertex and much larger than the momentum uncertainty then:

$$\sigma_t \approx \sigma_L^{secondary}/(\beta\gamma c)$$

The proper time resolution, σ_t, of the forward detectors in hadronic machines such as BTeV and LHCb is 40 fs while it is about 900 fs for the B-factories.

3.4 Performance of the displaced vertex trigger at CDF

The CDF silicon vertex trigger (SVT) has opened a new era of B-physics opportunities at a hadron collider machine. It consists of a real-time tracker capable of reconstructing 2D silicon tracks with the offline quality resolution that is an essential tool to discriminate $b\bar{b}$ and $c\bar{c}$ from

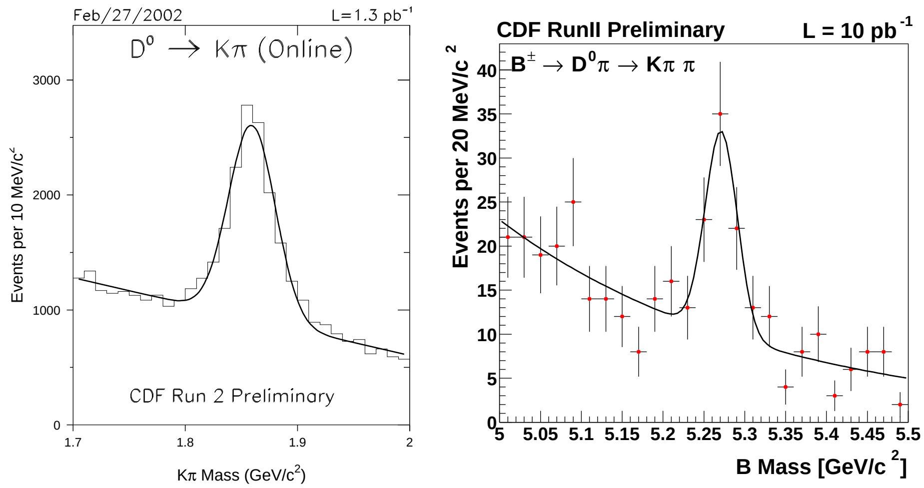

Figure 3: Left: The $D^0 \to K\pi$ invariant mass distribution measured online at CDF. Right: $B \to D^0\pi$ invariant mass distribution in decays collected with the SVT trigger.

hadronic background. The results obtained up to now are benchmarking the capability of the trigger but they are not yet fully representative of the physics that this triggers will make possible.

The CDF trigger has a three level architecture. At Level 1 the decision taken within 5.5 μs is based on objects such as electrons, muons, jets and tracks. The tracks are reconstructed by the extremely Fast Tracker (XFT), an asynchronous, parallel and pipelined track processor that reconstructs the tracks on the plane transverse to the beam by using the information of the open cell drift chamber (COT). At Level 2 the SVT takes the list of tracks found by the XFT and adds to this the information from four layers of the silicon detector. The results of the association of the silicon hits to each XFT tracks yield the track parameters (d_0, ϕ, p_t) with almost offline resolution. The impact parameter d_0 of the track with respect to the beam spot is then used to select events with displaced vertices. During the beginning of run II CDF has used the level-1 and level-2 track processors to select events that have two tracks with impact parameter larger than 100 μm and decay length in the transverse plane greater than 200 μm. The trigger has been performing well. Currently the Run II luminosity has been about 10^{31} cm^{-2} s^{-1} and the Level-1 rate is ≈ 3 KHz and the level 2 rate is 50 Hz. When the luminosity will increase further cuts will have to be introduced to keep the rate at an acceptable level.

The cross section for charm is large and CDF can monitor the SVT performance by reconstructing $D^0 \to K^-\pi^+$ online. The trigger has also allowed CDF to collect $B \to h^+h^-$ where h is a kaon or pion candidate and $B \to D^0\pi$ events. The online D^0 mass peak and the invariant mass distribution of $B \to D^0\pi$ candidates are shown in fig. 3.

4 Crucial measurements

In order to evaluate the reach of hadronic machines a series of specific measurements such as $\sin 2\beta$, measurement of B_s mixing and the determination of α and γ will be discussed.

4.1 B_s mixing

The B_s is unique to hadron colliders and therefore one of the physics goals of the Tevatron is to measure in detail the B_s mixing amplitudes including x_s, $\Delta\Gamma_s$ and the B_s mixing phase $\phi_s = -2\beta_s$.

These measurements are crucial not only in terms of checking the CKM unitary triangle but also because they are expected to be sensitive to physics beyond the standard model.

The measurement of the ratio of the B_s and B_d mixing frequencies x_s and x_d would benefit enormously the determination of the right side of the bd unitarity triangle R_t since:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2} \frac{F^2_{B_s} B_{B_s}}{F^2_{B_d} B_{B_d}}$$

In fact the measurement of x_s will constraint the right side of the unitary triangle to better than 6% since the uncertainties on the hadronic matrix elements partially cancel in the ratio $\xi = F_{B_s}\sqrt{B_{B_s}}/F_{B_d}\sqrt{B_{B_d}}$. The world average which is dominated by the LEP and SLD constrains Δm_s to be > 19 at 95 % confidence level (CL). Analyses of the unitary triangle[12] predict $22 < x_s < 30.8$. To measure such a rapid oscillation frequency, excellent decay time resolution is crucial.

Semileptonic decays such as $B_s \to D_s \ell \nu$ suffer from a large smearing of the decay time resolution due to the the missing neutrino momentum and can only probe up to $x_s = 30$ with 2 fb^{-1}. Better performance can be obtained by studying hadronic decays such as $B^0 \to D_s^- \pi^+$ that can be triggered upon using secondary vertex triggers. The current CDF II silicon detector is expected to achieve at least a proper time resolution of 60 fs. The ct resolution could improve to 45 fs if the low mass silicon layer closer to the beam pipe (L00) can be effectively integrated. Currently this layer is not used in the tracking. The flavor tagging effective efficiency in B_s decays is expected to be about 11.3 % at CDF in Run II.

For x_s the expected reach depends strongly on the number of B_s events that can be reconstructed in the $B_s \to D_s^- \pi^+(\pi^+\pi^-)$ samples, the S/B, the ct resolution, the effective b tagging and the SVT efficiency. In the most optimistic scenarios with $N(B_s) = 75,000$, ϵD^2=11.3 % and S/B=2 CDF expects to probe up to x_s of about 74 with 2 fb^{-1} of data. This expectation decreases to x_s of about 50 in a more pessimistic scenario. The CDF reach with L00 is shown in figure 4.

The statistical error on x_s is related to the statistical error on the observed mixing amplitude, therefore once a measurement of x_s is obtained at the 5 σ level the $\sigma(x_s) = \frac{1}{5\sqrt{2}}$ and $\sigma(x_s)/x_s <$ 1%.

BTeV and LHCb will obtain a similar sensitivity to x_s. For example BTeV expects to observe any value of x_s less than 75 in one year of running which is equivalent to 2 fb^{-1}. Therefore we expect that once x_s is observed then it will be measured very easily and precisely.

4.2 The determination of $\sin 2\beta$

The angle β can be determined by studying many different types of b decay modes. The best determination of $\sin 2\beta$ can be achieved by studying color suppressed decays such as $b \to c\bar{c}s$. The golden mode is the decay $B^0/\bar{B}^0 \to J/\psi K^0_s$ since the dominant penguin contribution has the same weak phase as the tree amplitude[10]. The only term with a different weak phase is suppressed by $\mathcal{O}(\lambda^2)$. Therefore the extraction of β from the measurement of the asymmetry in $B^0/\bar{B}^0 \to J/\psi K^0_s$ suffers negligible theoretical uncertainties.

At hadron colliders the golden mode $B \to J/\psi K^0_s$ is especially interesting experimentally because the $J/\psi \to \mu^+\mu^-$ decay mode gives a unique signature and allows for a powerful trigger. Therefore the decay $B^0 \to J/\psi K^0_S$ can be reconstructed with an excellent signal to background ratio. The interference of the direct decays $B^0 \to J/\psi K^0_S$ and $B^0 \to \bar{B}^0 \to J/\psi K^0_S$ gives rise to a CP asymmetry that measures $\sin 2\beta$:

$$A_{CP}(t) = \frac{\bar{B}^0(t) - B^0(t)}{\bar{B}^0(t) + B^0(t)} = \sin 2\beta \sin \Delta m_d t$$

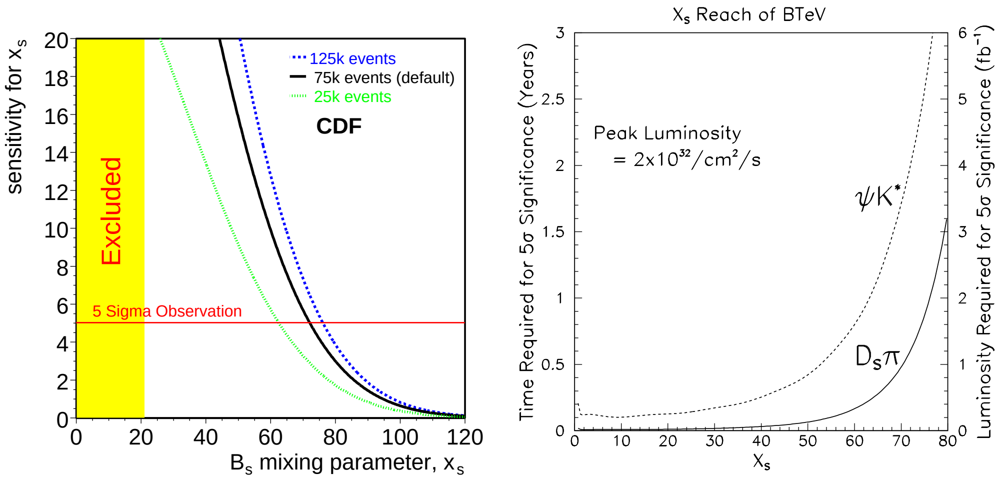

Figure 4: Left: The x_s reach of BTeV for different assumptions of the even yield. The curve assumes a $S/B = 1$ and ct resolution of 60 fs. Right: The x_s reach of the BTeV detector. The curve indicates the time needed to make a 5σ measurement.

This formula neglects the possibility of any direct CP violation which will introduce a term dependent on $\cos\Delta m_d t$. The time integrated asymmetry is:

$$A_{CP} = \frac{x_d}{1+x_d^2}\sin 2\beta$$

To measure the asymmetry we have to identify the flavor of the B meson at the time of production. The statistical uncertainty on $\sin 2\beta$ is inversely proportional to $\sqrt{\epsilon D^2}$ and to $\sqrt{S^2/(S+B)}$ where S is the number of signal events and B is the number of background events within three standard deviations of the B mass. Therefore the data sample should be chosen to maximize the signal and minimize the background. CDF measured $\sin 2\beta = 0.79^{+0.41}_{-0.44}$ (stat + sys) using the run I data sample [11]. Recently the Run 1 data sample has been re-analyzed to improve the tagging performance. The latest CDF value of $\sin 2\beta$ is $0.91^{+0.37}_{-0.36}$ (stat + sys).

In run II CDF expects to improve the effective tagging efficiency from $\epsilon_{eff} = (6.3 \pm 1.7)$ % to ≈ 9.1 %. The number of reconstructed $B \to J/\psi K_s^0$ is expected to increase because of the increase in the center of mass energy of the Tevatron from 1.8 to 1.96 GeV/c^2, increased muon coverage, and lower di-muon momentum threshold in the trigger. Monte Carlo studies estimated an increase of a factor of 50 in the $J/\psi K_s^0$ yield over the 400 events found in run 1A. We expect this improvement to result in an conservative error $\sigma(\sin 2\beta) \approx 0.05$.

The D0 collaboration has also studied their run II capabilities for the measurement of $\sin 2\beta$. The result of their Monte Carlo studies shows an expected data sample of about 34,000 $B \to J/\psi K_s$ events in 2 fb^{-1}. They expect an effective tagging efficiency of about 10% and an error $\sigma(\sin 2\beta) \approx 0.04$.

BTeV at the Tevatron will reconstruct about 80,500 $B \to J/\psi K_s^0$ after running for one year at a luminosity of 2×10^{32} cm^{-2} s^{-1}. This yields an error on $\sin 2\beta$ of about 0.025.

The measurement of $\sin 2\beta$ will continue to be improved by ATLAS and CMS. The mode $B \to J/\psi K_s^0$ was considered as one of the LHC benchmark modes in a recent study [5]. Combining the statistical samples after 3 years of data taking by ATLAS and CMS with 5 years of running at LHCb we expect a statistical error on $\sin 2\beta$ of 0.005. This precision is an order of magnitude better than the expected statistical precision that the e^+e^- B-factory are expected to achieve by 2005 when they will have collected 0.5 ab^{-1}. The large data samples expected at the LHC will allow a probe for a direct CP violating phase. Fitting the data with an additional term degrades the precision on $\sin 2\beta$ by ≈ 30 %.

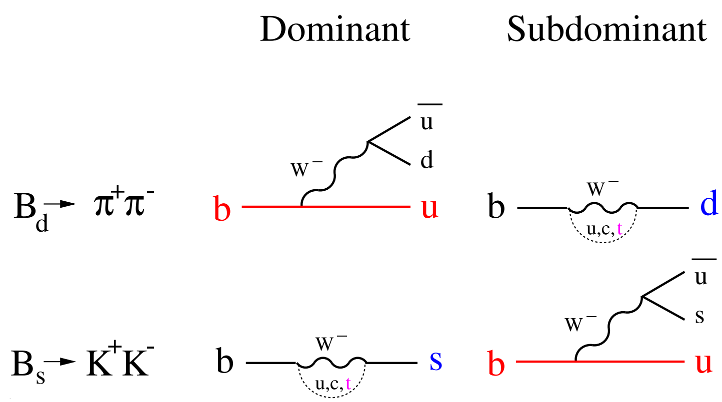

Figure 5: Left: The x_s reach of BTeV for different assumptions of the even yield. The curve assumes a $S/B = 1$ and ct resolution of 60 fs. Right: The x_s reach of the BTeV detector. The curve indicates the time needed to make a 5σ measurement.

4.3 Determination of α and γ

The decay $B \to \pi^+\pi^-$ could have been a powerful probe to determine α. It is now well established that extracting α from $B \to \pi^+\pi^-$ is limited because of so called " penguin pollution". This reaction can proceed via both the tree and penguin diagrams shown in fig. 5. The current experimental measurements $B(B^0 \to K\pi) \approx 1.88 \times 10^{-5}$ and $B(B^0 \to \pi^+\pi^-) \approx 0.47 \times 10^{-5}$ indicates that the penguin amplitudes can not be neglected. A large number of strategies[13] have been developed to disentangle the penguin and tree contributions and provide a measurement of α. One of the best known approaches was developed by Gronau and London[14]. It makes use of the isospin relation:

$$\sqrt{2}A(B^+ \to \pi^+\pi^0) = A(B_d^0 \to \pi^+\pi^-) + \sqrt{2}A(B_d^0 \to \pi^0\pi^0)$$

and its CP-conjugate which form two triangles in the complex plane. This approach relies on the determination of $B(B_d^0 \to \pi^0\pi^0)$ which is expected to be of $\mathcal{O}(10^{-6})$ and is very difficult to measure. Since the π^0 mesons in this decay are energetic, the opening angle between the two photon is small and therefore they tend to overlap in the electromagnetic calorimeter.

Other methods include the mode $B \to \rho\pi$ and the study of the CP asymmetries $B_s \to K^+K^-$ and $B_d \to \pi^+\pi^-$. The final state $\rho\pi$ offers the advantage of having a relatively large branching fraction. Furthermore since the ρ is spin 1 while the B and π are spinless, the ρ is fully polarized in this decay which should help in maximizing the interference and therefore achieving a better error. The BTeV collaboration following the technique proposed by Snyder and Quinn[15] expects to be able to measure α with a sample of 1000-2000 background free, flavor tagged events.

The CDF collaboration plans to use the decay modes $B^0 \to K^+\pi^-$, $B_s \to K^+K^-$, $B^0 \to \pi^+\pi^-$, $B_s \to \pi^+K^-$ and SU(3) flavor symmetry to measure γ. Based on measured B^0 branching ratios and the production fractions $f_s(f_d)$ for $B_s(B_d)$ we expect an event ratio of:

$$(B^0 \to K\pi) : (B^0 \to \pi\pi) : (B_s \to KK) : (B_s \to \pi K) = 4 : 1 : 2 : 0.5$$

Using the latest measurement of the B cross section[16] CDF expects between 5000 and 9000 fully reconstructed $B^0 \to \pi\pi$ events in 2 fb^{-1}. To study the reach in γ CDF assumes that 5,000 $B^0 \to \pi\pi$, 20,000 $B^0 \to K\pi$, 10,000 $B_s \to KK$ and 2,500 $B_s \to \pi K$ will be reconstructed. CDF expects to extract the physics components from the background by making use of the invariant mass resolution and the dE/dx information provided by the open cell drift chamber. Two of the four modes of interest are self tagging ($B^0 \to K^\pm\pi^\mp$ and $B_s \to K^\mp\pi^\pm$) while two are CP eigenstates ($B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$). CDF expects to measure the time dependent CP

asymmetries in $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ which are given by:

$$A_{CP} = A_{CP}^{dir} cos\Delta mt + A_{CP}^{mix} sin\Delta mt$$

Following Fleisher[17] the unitarity angle γ can been extracted from the measured time dependent asymmetries by using the U-spin symmetry that relates $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$. In the limit of U-spin symmetry the strong phase θ and the penguin to tree ratio d in $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ (denoted by $'$) are connected by:

$$\theta' = \theta \qquad\qquad d' = d\frac{1-\lambda^2}{\lambda^2}$$

The measured time dependent asymmetry can be used to extract β, γ, d and θ. The error in γ varies between 6 to 15 degrees depending to the value of d which is assumed to vary between 0.1 and 0.5.

5 B_s decays

The decay $B_s^0 \to J/\psi\phi$ is the B_s counterpart to the "golden mode" $B_d \to J/\psi K_s$. Since the J/ψ and ϕ are vector mesons, the CP parity of the final state is a mixture of different CP even and odd contributions and the CP asymmetry may be diluted by possible cancellations. It is possible to disentangle the CP odd and CP even contributions through an angular analysis of the decay products $B_s^0 \to J/\psi(\ell^+\ell^-)\phi(K^+K^-)$. An interesting feature is that in the standard model we expect CP violation in this mode to be small. Therefore it is a sensitive probe for new physics. This mode can also provide information on the mixing parameter $\Delta\Gamma_s$, Δm_s and the weak phase $\beta_s = \arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$. ATLAS, CMS and LHCb have studied this decay mode extensively. ATLAS and CMS expect $300,000$ and $600,000$ events respectively after the first 3 years of operation. LHCb expects 370,000 event after 5 years of LHC running. The result of the studies[5] show that $\Delta\Gamma_s$ can be measured with a precision between 8 to 12 % for $\Delta\Gamma_s/\Gamma_s = 0.15$. The mode appears to be sensitive to probing models of new physics such as the left-symmetric model with spontaneous CP violation and the isosinglet down quark mixing model[18].

The study of the time dependent CP asymmetry in $B \to J/\psi\eta(')$ is another powerful test for new physics. This decay probes the angle β_s which is estimated to be about 0.02 in the standard model without the cancellations that are possible in $B_s^0 \to J/\psi\phi$. Silva and Wolfenstein[19] have pointed out that a measurement of α, β and γ could miss new physics. For example if new physics arises in $B^0 - \bar{B}^0$ mixing through a new phase θ^{NP} then a measurement of the phase in $B^0 \to J/\psi K_s$ will yield $2\beta' = 2\beta + \theta^{NP}$ while a measurement of α using $B^0 \to \pi^+\pi^-$ (after eliminating the penguin pollution) will measure $2\alpha' = 2\alpha - \theta^{NP}$. In this case we would miss the new physics since $2\alpha' + 2\beta' = 2\alpha + 2\beta$ and therefore $\alpha' + \beta' + \gamma = 180°$. The measurement of β_s would instead clearly check the standard model since an observation of an asymmetry larger than $\mathcal{O}(\lambda^2)$ will be an unambiguous signal for new physics.

The decay $B \to J/\psi\eta(')$ is very challenging and requires excellent photon reconstruction capabilities. The BTeV experiment will have an excellent electromagnetic calorimeter and it expects to measure β_s with an error $\delta\beta_s$ =0.024 after one year of running[20].

6 Outlook and prospects

The two asymmetric B-factories, PEP-II and KEKB, have achieved reliable operation at high luminosities of a few 10^{33}cm^{-2}s^{-1} in a remarkably short period of time after their startup. These luminosities have enabled their experiments, *BABAR* and Belle, respectively, to observe *CP* violation in the decays of the B^o meson. Operational experience with both machines has

Table 1: Comparison of *CP* Reach of Hadron Collider Experiments and Super*BABAR*. The last column is a prediction of which kind of facility will make the dominant contribution to each physics measurement.

	CDF 2fb^{-1}	D0 2fb^{-1}	BTeV 10^7s	LHCb 10^7s	*BABAR* Belle (2005)	10^{35} 10^7s	10^{36} 10^7s	
$\sin 2\beta$	0.05	0.04	0.011	0.02	0.037	0.026	0.008	Equal
$\sin 2\alpha$			0.05	0.05	0.14	0.1	0.032	Equal
$\gamma\,[B_s(D_sK)]$	$\sim 25^o - 45^o$		$\sim 11.5^o$					Had
$\sin 2\chi$			0.024	0.04	-	-	-	Had
$\text{BR}(B \to \pi^o\pi^o)$			-	-	$\sim$20%	14 %	6%	e^+e^-

now led to plans to setup super-B-factories operating at $10^{35}\text{cm}^{-2}\text{s}^{-1}$. The hadron collider experiments at the Tevatron, CDF and D0, are beginning to produce B physics results that will complement the B-factories. Dedicated experiments at the Tevatron and the LHC, BTeV, and LHCb, and the two large general purpose experiments at the LHC, CMS and ATLAS, will begin to contribute at very high levels of sensitivity to the study of *CP* violation and rare decays in the B system, starting around 2007. Proposal for a "Super B-factory" with a luminosity goal of $10^{36}\text{cm}^{-2}\text{s}^{-1}$ are under discussion.

The reach of these future experiments has been studied at Snowmass [21] and it summarized in table 1.

It is clear that the 10^{36} e^+e^- machine can compete with the hadron collider experiments on many interesting *CP* violating decays and on rare decays of B_d and B_u. It should do better on decays involving τ's and missing ν's since the hermeticity and energy constraints provided by running at threshold permit one to establish the neutrino's presence in the event by demonstrating a recoil mass consistent with zero. The experiments at hadron collider will continue to have better reach in the study of B_s physics. This is a strength of the hadron collider experiments. The e^+e^- experiments also do not have high enough energy to study b-baryons or B_c mesons. Therefore the hadron and B-factories will be complementary and both will be needed for an exhaustive precision probe of the consistency of the flavor changing sector of the standard model and in searches for New Physics.

7 Acknowledgments

I would like to thank the organizing committee for this conference which brought together particle physicists and cosmologists in a beautiful setting.

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